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LED Failure Modes Implications in Ex-e Applications

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Abstract: Design reliable and safe LED (light emitting diode) lighting equipment for potentially explosive atmospheres should require knowledge about the possible failure modes of LED sources. Nowadays, LED technology potential is not adequately considered by IECEx (International Electrotechnical Commission system for certification to standards relating to equipment for use in explosive atmospheres) yet. Standards only consider LEDs adequate for Zone 1 when luminary is realized by the Ex-d protection strategy, or if a big limitation in terms of power is guarantee, for Ex-i mode. In particular, Ex-d LED luminaries are obtained by using heavy, thick and expensive flameproof enclosures, entrusting safety only to the mechanical strength of the case. Luminous efficiency's also reduced since the glass used is very thick (10% reduction of approximately every 10 mm of thickness of the glass). The paper shows a study about different possible causes of LED failure and their implication with explosive atmospheres, investigating whether LED technology can be used safely with other safety strategy like Ex-e, which can guarantee better performance and less cost.

Key word: Luminaries, power LED, failure modes, Ex, ATEX (ATmosphères ed EXplosibles), IECEx, luminous efficiency, thermal dissipation.

1. Introduction

In the world of industry, LED (light emitting diode) technology stands today, thanks to its characteristics, better than regular light sources. The key of LED's success is to be found in two basilar benefits that can offset their still high cost [1]:

- low power consumption, that allows both electrical energy saving and installation of lower protection and small section cables;
- high number of operating hours, that permits save on the hourly cost of the LED lamp and on maintenance costs.

Particular industrial sectors like petrochemicals or mining, need special electrical equipment due to potential explosive atmospheres present here. An explosion is allowed by contemporary presence of three elements: fuel, combustive agent (oxygen) and an ignition source. These are represented by the explosion triangle of Fig. 1.

The explosion cannot occur if even just one of these three elements is not present. Therefore, different modes of protection can be implemented, depending on the type of load to be protected. They're based on three different principles, which act differently on the three elements of the triangle: containment, prevention and segregation.

In the containment method, the parts that can cause ignition are included in a box made to withstand the pressure of the explosion, preventing the spread of flame.

In the prevention method, necessary measures are taken to avoid excessive temperatures and creation of sparks, thus eliminating the ignition source.

In the segregation method, active components are separated from explosive mixture using resins, sand, oil, preventing any contact with oxygen and fuel.

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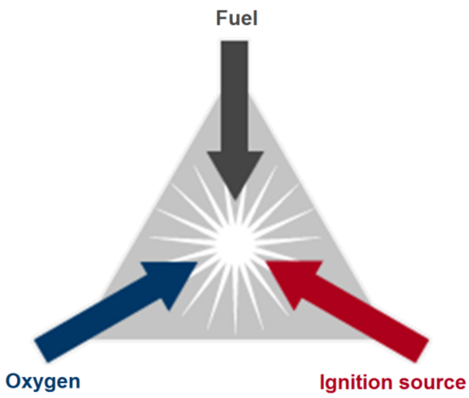

Fig. 1 The explosion triangle.

The modes of protection born from these three different principles.

LED behavior in fault condition is not yet fully known, so this technology is already installed in these system but with huge limitation. Today IECEx (International Electrotechnical Commission system for certification to standards relating to equipment for use in explosive atmospheres) consider two main protection strategies for LED lighting fixtures for Zone 1 defined Ex-d [1] (containment principle, is adopted the same protection strategy designed for traditional light sources (Fig. 2)) and Ex-i [2] (with a big limitation in terms of voltage and installed power, prevention principle (Fig. 3)), at the moment, except the standard on LED for normal use, there are no other reference about it. For example, taking into consideration the IEC60079-7 (Ex-e [3] mode of protection, prevention principle) LEDs are not considered, even if this protection strategy can be very useful for LEDs (Fig. 4).

[1] In Ex-d, parts which can ignite a potentially explosive atmosphere are surrounded by an enclosure which withstands the pressure of an explosive mixture exploding inside the enclosure itself, and prevents the transmission of the explosion to the external atmosphere surrounding the enclosure.

[2] In Ex-I, additional measures are applied to the electrical equipment to increase the level of safety, thus low voltage and low current and then maintaining the energy level in electrical circuits in the flammable atmosphere below a level that could cause ignition.

[3] In Ex-e, additional measures are applied to the electrical equipment to increase the level of safety, thus preventing excessive temperature development and the occurrence of sparks or electric arcs within the enclosure or on exposed parts of electrical apparatus, where such ignition sources should not occur in normal service.

Therefore, the majority of LED lighting systems for explosive atmospheres are realized using Ex-d strategy but luminaries Ex-e can guarantee considerable advantages in comparison to the same Ex-d ones [2], as:

- economic advantages: the box have not to contain the explosion, so the thickness of Ex-e device is lower than Ex-d device (about 1:10), and in the same way, the cost of material;
- luminous efficiency: Ex-e use less thick glasses than Ex-d and it permit higher optical performance at the same installed power;
- installation: Ex-e devices installed at different heights guarantee an easier and safer installation than heavy equipment Ex-d.

Fig. 2 Example of Ex-d LED luminaries.

Fig. 3 Example of Ex-i LED luminaries.

Fig. 4 Example of hypothetical Ex-e LED luminaries.

Apparently, LED technology offers great mechanical strength and stability. Goal of this paper is to analyze the possibility of using LEDs in Ex-e luminaries in every restricted area, included Zone 1. To do so, it will be study the behavior of LEDs in case of failure, not for confirm reliability and durability of LED sources, but rather to ascertain the possible causes of failures, that could be the ignition source of an explosive atmosphere.

2. Led Technology

LED is a special type of diode that emits electromagnetic radiation in UV, infrared or visible spectrum range when is transited by continuous electric current, based on the principle of electroluminescence. Like a regular diode, this is a one-way device equipped with electric terminals called anode (positive) and cathode (negative). The core of the device, called chip, is a p-n solder joint, or a crystal consisting of two peripheral areas made up from the same semiconducting material doped differently.

The solder joint is made of materials such as GaAs (gallium arsenide), GaP (gallium phosphide), InP (Indium phosphide), GaN (gallium nitride) or alloys such as AlGaAs, AlGaP, GaAsP, GaAsInP, AlInGaP or AlInGaN. Based on the material used, it is possible to obtain various colors for the light emitted (Fig. 5), different current-photons conversion performance and also different production costs [1, 3].

There are various types of LEDs with different structures and features, below are described the four types that are currently present on the market.

2.1 LED THT

The LEDs with THT (through hole technology) were the first manufactured on a commercial level at the end of the 60 s. These are the classic LEDs with capsule lamp, with diameters ranging from 3 mm to 5 mm that were usually used as pilot lights or infrared signals (remote controls, data transmitters) and, sometimes, for lighting, but with a relatively reduced power for a single device. Their main feature consists in the contacts (anode and cathode) made up of metal wires that upon installation are inserted into the printed circuit slots and welded. These LEDs have the chip welded and electrically connected to a metallic reflective net that continues the metallic filament that makes up the cathode. The chip is connected to the anode by means of a narrow gold wire. The structure is enclosed in an epoxidic plastic resin. The LEDs can have various colors, depending on the chips used (with different anodes) within the same case. Therefore, there are LEDs with capsule lamps that feature three or four terminals (Fig. 6) [3].

2.2 LED SMD or SMT

The LEDs SMD (surface mounted device) or SMT (surface mounted technology) have been developed directly from the THT LEDs. In this technology, the electrical connection terminals are placed to the side of the case and are made up of small metallic plates. The

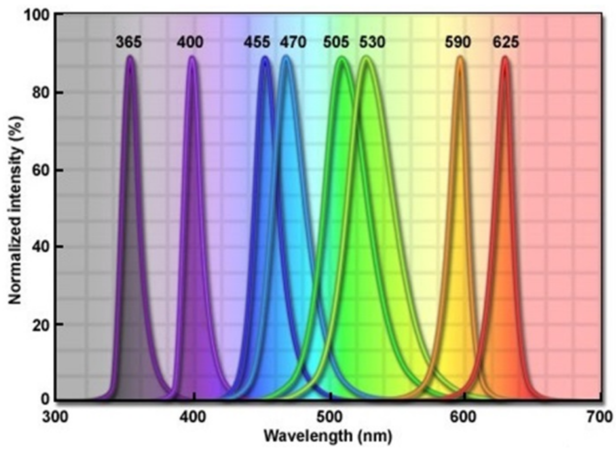

Fig. 5 Electromagnetic emission spectrum of LEDs.

Fig. 6 LED THT.

SMD LED is welded directly to the surface of a printed circuit without drilling the latter. Welds are much smaller and are made directly by means of special machines on the same side on which the LED is placed. In Fig. 7, is shown an enlarged picture of this type of LED.

The device has small sizes, reduced at millimetric scale and is built by installing a chip into a low, square plastic case. The printed circuit used is much narrow than usual and in some cases is designed, so that it acts as a heat sink, being put into contact with the device.

The small sizes enable the SMD LED to be used in various applications such as TV monitors or indicator lights. The miniaturization enables inserting several chips inside the same case. Compared to THT LED, this type of LED enables heat dispersion for greater duration.

2.3 Power LED

The high luminous efficacy LEDs, also called Power LED (Fig. 8), can emit significantly greater luminous flux compared to previous models. This feature makes them suitable for industrial, public and private lighting. Inside the plastic or ceramic, case is installed one or more chips with sizes usually greater than normal sizes. The system is enclosed in a transparent dome made in silicon material and often surmounted by additional optical unit that focuses the light and protects the LED. The device contacts protrude sideways and, actually, the Power LED uses the latest SMD technology. The particular feature consists of the need to use a heat sink suitably dimensioned according to the power of the device, to keep the temperature of the LED below the limits set for the optimal operation of the device [3]. The Power LED is designed so that the metal base comes into contact with the chip, but, however, electrically isolated to lower the thermal resistance of the device and facilitate heat conveyance to the heat sink. In the case of moderate powers, this metal base is sufficient to act as a heat sink.

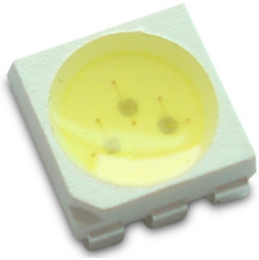

Fig. 7 LED SMD.

Fig. 8 Power LED installed on PCB (printed circuit board) star.

Many manufacturers included the use of printed circuit boards tailored for each Power LED device to optimize cooling, operation and installation. Thermal management is so important that some studies provide the use of alternative methods like cooling fluid or use of hemispherical lens, that can guarantee better heat dissipation [4-6].

2.4 Power LED Flip Chip

The connection technology for wireless micro electronic devices appeared at the end of the 60 s, but it was implemented in Power LED applications only in the last years. By using this system, also called “flip chip”, the core of the semiconducting material that makes up the p-n solder joint does not require gold filament (or filaments) for the electrical connection. The chip is connected “reversely”, therefore, the contacts of the epitaxial layers of the connection are both at the base of the chip and are welded directly to the anode and cathode located at the base of the case (Fig. 9) [7-9].

This technology boasts some benefits in terms of strength and performance. The structure provides LEDs resistance to vibrations and shocks five times greater compared to conventional devices. This translates into greater duration of the LED. Thermal dissipation is more efficient, approximately by 25%.

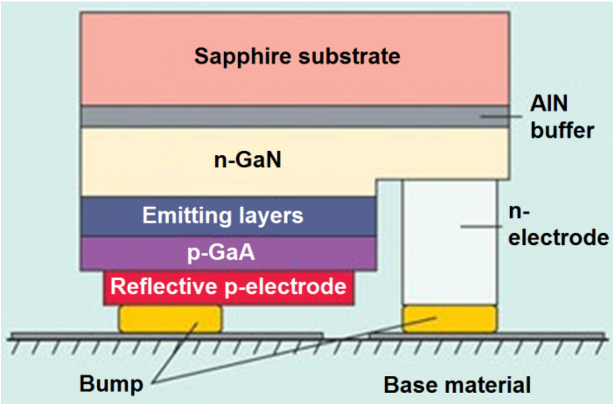

Fig. 9 LED flip chip scheme.

In Fig. 10, is shown a real picture of a LED flip chip, where you can see that, the gold wire is absent and the reversed position of cathode and anode. The structure of this LED is of ceramic type, which enables a better management of the heat developed by the chip itself.

The light in Power LED flip chip is emitted directly on the top layer of the chip [4].

Actually, reduced operating temperatures enable greater luminous efficacy. The absence of filaments enables a better light output because there are no shadows generated by the filaments [10].

3. Cause of Led Failure

LED and Power LED devices are very robust and reliable, especially when compared with normal light sources. Nevertheless, they are not free from faults or defects more or less serious, albeit increasingly rare and improbable compared to other types of lighting devices. The possible faults concern the outer case and internal components. The fault can be caused by extremely high current values or an excessive thermal stress or a stress of mechanical type. The main effects are a decrease in the luminous efficacy of the device and, in rare cases, complete rupture of the LED [11-13].

Below are examined all the possible causes of failure divided into the following two different families:

(1) failures on LED case:

- epoxy or silicon resin degradation;
- mechanical stress caused by deformation of the involucres;
- phosphor degradation.

(2) semiconductor and LED's metallic parts failures:

- nucleation and dislocation;
- electromigration;
- glass passivation;
- current crowding;
- ESD (electrostatic discharge);
- EOS (electrical overstress);
- reverse polarization;
- moisture and popcorn effect.

3.1 Failures on LED Case

3.1.1 Epoxy or Silicon Resin Degradation

The LED chip is protected by a transparent coating in epoxy or silicone plastic material. In the case of epoxy resin, this can turn yellow if subjected to excessive thermal stress and/or UV rays. The degradation of the material, known as "yellowing", leads mainly to a decrease in luminous efficacy of the device because certain wavelengths are absorbed by the resin (especially the short waves).

Use of silicon resin reduces these risks. But silicon resin also can be subjected to yellowing degradation by the absorption of chemically incompatible VOC (volatile organic compounds) combined to heat and high photonic energy (Fig. 11).

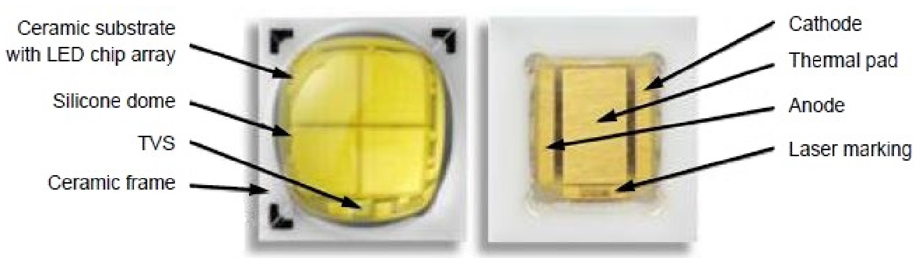

Fig. 10 Power LED flip chip (TVS: transient voltage suppressor).

(a) (b)

Fig. 11 (a) Silicon resin (new) degrade and turns yellow after (b) VOC exposition (after 100 h), decreasing luminous efficacy.

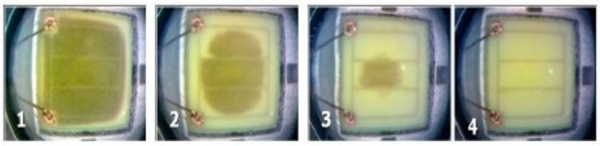

Fig. 12 LED can be cleaned out gassing VOC (2: after 24 h; 3: after 48 h; 4: after 72 h).

VOCs may be present in the atmosphere or in some components used for the luminaries, like O-rings. However, yellowing effect is reversible by outgassing the VOC, exposing LED in clean atmosphere (Fig. 12). VOC issues are reduced using secondary lens assemblies, proper materials (producers provide lists of compatible materials) and venting of the enclosure [14].

3.1.2 Mechanical Stress Caused by Deformation of the Involucres

The epoxy resin is a thermo-structured material which, when subjected to excessive heat that exceeds glass transition temperature, it quickly begins to expand, tending to convert into liquid state (typical pattern of an amorphous material). Incorrect application of additional optics or heating-cooling cycles can also damage the case (Fig. 13).

In the case of deformation and increase in volume, a mechanical stress, more or less intense, is applied to the internal parts of the device (lead wires, chips). In particular, the gold filament can deform until it breaks, causing an open circuit situation (Fig. 14).

This situation can become dangerous in the rare case where the outer casing breaks and cracks exposing the gold filament to the external environment [15]. In the case, where the wire is broken and the voltage and current are suitable, a spark may be generated between the two ends of the wire.

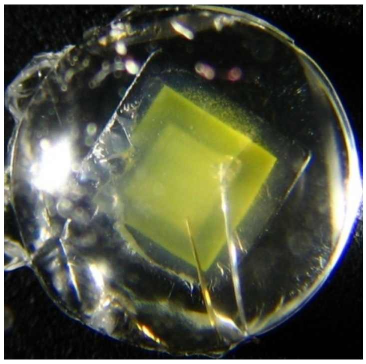

Fig. 13 Damaged casing due to excessive force applied on it.

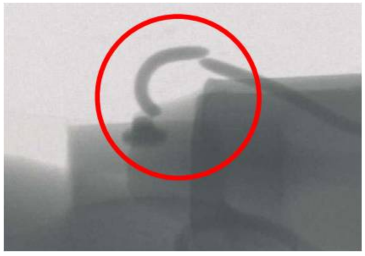

Fig. 14 X-ray inspection point out the wire's break.

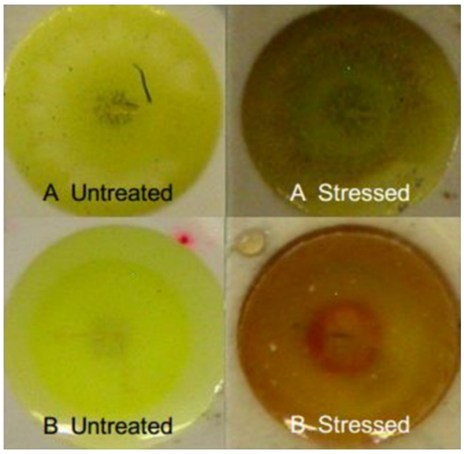

Fig. 15 Examples of accelerated aging tests on phosphor layers with application of high temperatures.

3.1.3 Phosphor Degradation

Temperature is a factor that affects not only the epoxy casing, but also the phosphors used in the Power LED to generate white light. Phosphors tend to degrade naturally and slowly over time, but, however, excessive temperature values may speed up the process, depending on the type and quality of phosphors used to manufacture the LED. Fig. 15 shows an example of accelerated aging test, where is clear the phosphor degradation.

3.2 Semiconductor and LED's Metallic Parts Failures

3.2.1 Nucleation and Dislocation

If we consider the problems related to semiconductor, the first characteristic phenomena related to a semiconducting material are nucleation and dislocation. Nucleation is one of the mechanisms through which a substance is crystallized. By this phenomenon, the number of crystals within a crystalline solid increases due to the aggregation of several particles. Dislocation is rather a defect in the crystal structure, since the regular structure of a crystal is not observed, but gradients are created within the crystal lattice itself. These two phenomena are highlighted by the heat and the increase in current density and require a pre-existing flaw in the molecular structure. Dislocation and nucleation lead to deteriorations that result in modifications more or less important in the operation and efficacy of the solder joint. Dislocations can create nano-holes which allow direct current passage in p-n junction without photon emission, decreasing efficiency (Fig. 16).

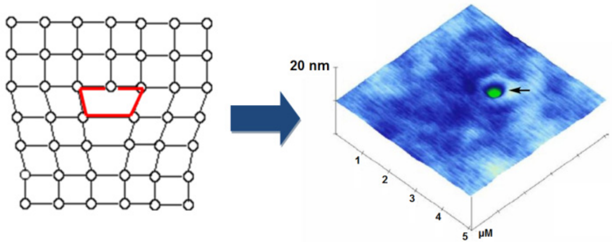

Fig. 16 Dislocation scheme and the resulting nano-hole at electronic microscopic inspection.

3.2.2 Electromigration

Electromigration consists in a transport of metal atoms, which are moved from their natural position, driven by the gradual motion of ions. Electromigration is caused by particularly high values of current density or excessive voltages and leads to the creation of defects in the joint. When these phenomena increase, the luminous efficacy of the device decreases, thus reducing the reliability of the LED as well. Working on wires, it could create open circuit (removing material) or short circuit (pile up material) (Fig. 17). Into LED capsule, wires are submerged in silicon resin and a short here is impossible. Attention should be placed outside over the electrodes. Good supply, insulation and distance between electrical part prevent damages.

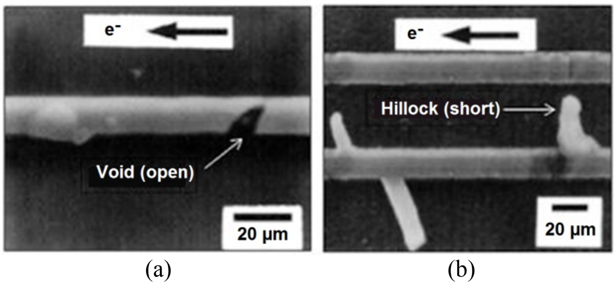

Fig. 17 Electromigration can cause (a) open circuit or (b) short circuit.

3.2.3 Glass Passivation

Some LED chips are processed through chemical processes with the aim to protect the edges of the solder joint, assuming a shape called "mesa" (from the Spanish "plateau") (Fig. 18). These structures are subjected to high leakage currents, and it is required, therefore, to proceed with the passivation of the material. If the passivation process is not performed correctly, the LED is likely to present small leakage currents and, therefore, reduced luminous efficacy, similarly to what happens in the case of microtubes generated by dislocations.

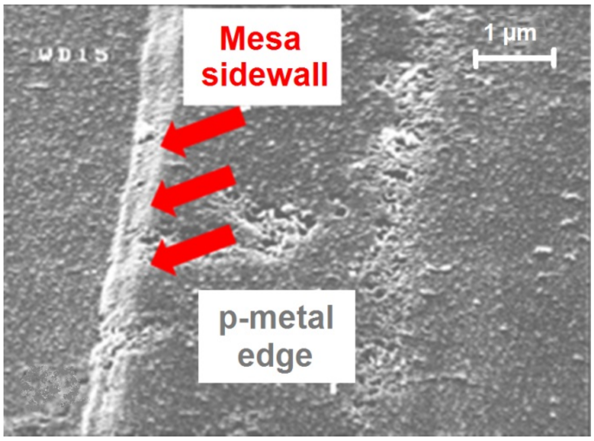

Fig. 18 Magnification of mesa sidewall.

3.2.4 Current Crowding

The phenomenon known as "current crowding" consists of a densification of current in localized points of the LED. Different resistance values of chip's layers cause the current to be no uniform and amass near the edge of the contacts. In fact, the defects are present especially next to the metal contacts, like in Fig. 19, due to incorrect welding, or inside the p-n joint due to pre-existing inconsistencies of the material itself. The different distribution of the current results in peak currents expressed in mA and creates hot spots which decrease the luminous efficacy of the LED [16].

3.2.5 ESD

When handled, the LEDs are subjected to electrostatic discharges, like all normal microelectronic devices. In general, a reverse biased ESD pulse can damage catastrophically the LED, instead a direct biased pulse will pass, generally, without damage [17]. This peak generates very high localized heating in the layers of the solder joint that damage it and lead to deviations of the normal optical-electric parameters of the device. In the worst cases, the chip may perforate, creating an open circuit or even short circuits (Fig. 20); if the heat generated melts the chip until it creates a metallic contact [18].

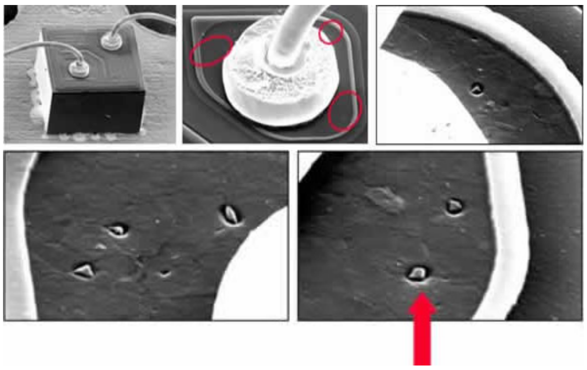

Fig. 19 Magnification of hot spots caused by current crowding.

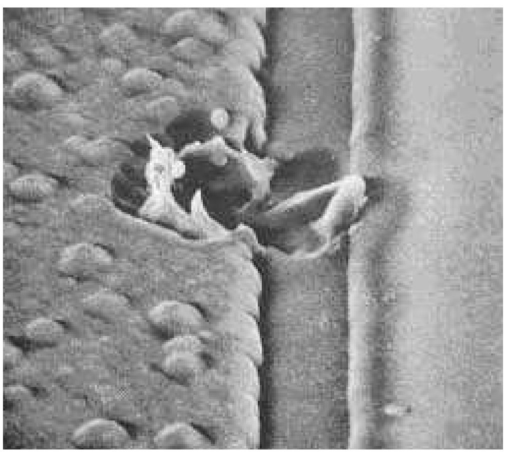

Fig. 20 Chip's perforation caused by ESD.

3.2.6 EOS

Excess voltages or currents may also result from incorrect supply voltage of the LED device or failure of the power supply. Particularly intense over-current lasting from 100 ns to 1 ms during LED operation is likely to heat up the device excessively, compromising its structure. Once the gold, very thin, conducting filament has reached a certain temperature, it burns and at last it melts, opening the electrical circuit (Fig. 21). Near components like phosphor or silicon resin can be damaged [19].

Electric stress can degrades the performance of the LEDs even more than an external thermal stress, because the temperature rises suddenly [17, 20].

3.2.7 Reverse Polarization

Any LED, like any regular diode, consists of a p-n solder joint and cannot be subjected to excessive reverse voltage. Depending on the type and design features of every LED, the manufacturer provides the limits that, if not complied with, lead to joint breakdown. In Fig. 22, is shown an indicative voltage-current graph of a normal diode, corresponding to that of LED.

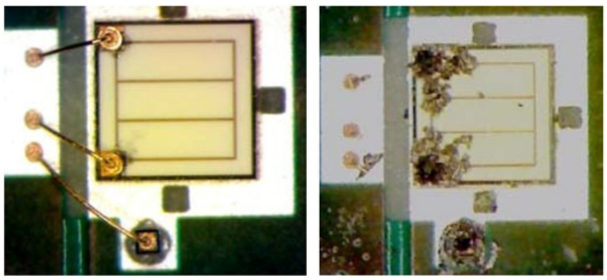

Fig. 21 EOS effects on LED chip and wire bonds.

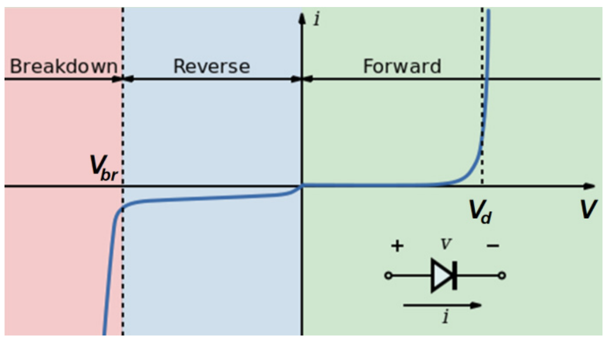

Fig. 22 Diode's voltage-current graph. Diodes and LEDs can tolerate reverse voltage and current until breakdown limit.

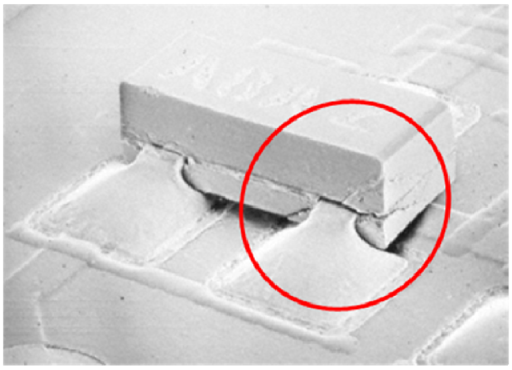

Fig. 23 Cracks due to popcorn effect.

3.2.8 Moisture and Popcorn Effect

During manufacturing, if heat is applied suddenly and unexpectedly to the printed circuit, the moisture accumulated inside the circuit may evaporate around 100 °C. Transition to gaseous state implies an increase in volume and if the gas does not find a vent, the circuit is inflated until failure (this is why it is called “popcorn effect”) (Fig. 23).

3.3 Conclusion of the Failures Analysis

So far, we have analyzed all the possible failures for the LEDs currently available on the market. We shall further clarify the situation of failure and the possible consequences on different types of LEDs, described above. In Table 1 are given, in the columns, the four different types of LEDs, and in the rows the possible faults (with reference to the previous sections).

In Table 1, for each type of LED, is reported the relative failure defining the possible consequence with the following letters:

d → degradation;

oc → open circuit;

sc → short circuit;

x → none.

According to the constructive characteristics of each LED’s family, after the degradation of their performance, could happen an open circuit condition or a short circuit condition. For flip chip LED, is not possible to have open circuit condition, because there is no gold filament.

Only open circuit condition is represented by “moisture and popcorn effect” failure, but it is imputable to PCB and not to LED and only during manufacturing.

The short circuit condition can happen with particularly intense electrostatic discharge, depending also on the size and strength of the specific LED. A short circuit may also occur if metallic filaments are created from SMD LEDs metallic paste, and come into contact with other metal parts. Not to be confused with “microscopic” short circuits that consist in leakage currents that only reduce the efficacy of the LED in the case of dislocation and insufficient glass passivation.

The most severe fault conditions to be taken into account, especially in potentially explosive environments, are those that create an open circuit. In fact, the degradation conditions lead exclusively to a reduction in LED efficacy, but not to hazardous explosion triggering conditions and the short circuits can be prevented by using simple fuses that can be already integrated into the Power LED.

Considering a similar probability of failure, the flip chip LED presents a lesser number of open/short circuit conditions, and, therefore, possible trigger of minor sparks or/and high temperature. These conditions can only occur for failures B.5, B.6 and B.7.

Unlike the other three types of LEDs, the flip chip LED is mainly degraded in terms of optical efficacy, this is mainly due to the total absence of the internal gold filament which ensures intrinsic safety of the device.

Table 1 Consequences of LED failure.

	LED THT	LED SMD	Power LED	FLIP CHIP
A.1	*d*	*d*	*d*	*d*
A.2	*oc*	*oc*	*oc*	*x*
A.3	*x*	*x*	*d*	*d*
B.1	*d*	*d*	*d*	*d*
B.2	*oc*	*oc*	*oc*	*d*
B.3	*d*	*d*	*d*	*d*
B.4	*d*	*d*	*d*	*d*
B.5	*oc-sc*	*oc-sc*	*oc-sc*	*sc*
B.6	*oc-sc*	*oc-sc*	*oc-sc*	*d-sc*
B.7	*oc-sc*	*oc-sc*	*oc-sc*	*sc*
B.8	*x*	*oc*	*oc*	*oc*

4. Conclusions

LED technology still demonstrates its goodness in terms of quality, stability and reliability [21, 22]. High security is offered by intrinsic structure including low current and voltage values needed to supply.

Most of failures refer to atomic structure problems of materials used and manufacturing. In addition, these are failures that not affect safety of device but only its efficiency. Annoying problem could be the yellowing caused by VOC. Moisture present in industrial atmospheres could contain for example hydrocarbons that can discolor the resin. Also in this case, only luminous efficacy is decreased, not safety, but it is "on field" problem and not of manufacturing. To reduce the issue, is sufficient using proper materials and guarantee good ventilation inside the luminaries. However, cases are provided with gaskets and external vapor and dust could not enter inside the enclosure in normal condition.

Real problems could arise at electrical and thermal level. The possibility of arcs and sparks is already unlikely, but into the LED, a spark could appear only if the wire is exposed after package cracking. However, other electric arcs can start out of LED, at the contact and drive level. Good insulation and implementation of small and cheap electronic devices, protect the LED from over current and overvoltage coming from supply, or even by electrostatic discharge, ensuring the absence of sparks. Focusing on LED, this hazard can also be prevented using Power LED with "flip chip" technology in which the internal filament (gold wire) is absent. This type of Power LED is extremely solid and strong, and also improve thermal dissipation. Therefore, it could be useful to build smaller enclosures with less expensive cooling systems. This allows the "flip chip" Power LEDs to be efficiently used, together with other protective devices such as fuses, for Ex-e equipment, that should not generate electric arcs or sparks.

The problem of reliability, and then the lifetime, was not analyzed because it is not the goal of this paper, but it is very important to take in consideration [23, 24]. Give an exact value of failure rate for every failure is difficult because every LED or LED system is different, how different is the atmosphere in which they are exposed.

It is necessary to point out the different definition adopted for lifetime for devices used in ordinary location and in hazardous location. In the first case, producers often use, for the sake of simplicity, only lumen maintenance to define LED (or LED system) lifetime, which also reaches one hundred thousand hours [25, 26]. Instead for hazardous location, it would be better to analyze the problem in a more comprehensive way, combining lumen maintenance with probability of principal failures. Some LED manufacturers do that on their LED or LED arrays, using data from different stress tests and applying statistical methods. The probability of failures, if the manufacturer's instructions are followed, is very low and that confirms the quality of LEDs. A life cycle also superior to 50-60,000 h can generally be guaranteed.

The problem of reliability is very complex when a hazardous location is occurred, because from the reliability depends, the possibility to use or not the LED in Ex zone. The standards Ex do not talk about this problems and there are no information in bibliography (the stress tests made by LED producers are not designed for heavy conditions of Ex areas and they are not made on complete luminaries). To evaluate the reliability of the LED technology in order to determine the safety integrity through knowledge of LED failure rates and failure modes could be possible to adopt the instruments required in assessing SIL (Safety Integrity Level) for equipment according to the IEC/EN61508, which has already been adopted for a number of equipment, components and sub-systems used in the functional safety field. It is well known that, some devices can be used as active control of dangerous sources, with a real and expected level of reliability, if they have been qualified according to the IEC/EN61508. Further proof of what expressed above is the ATEX (ATmosphères ed EXplosibles) European harmonized standard EN50495:2010, which defines the integrity level of the functional safety of active control systems and compares it with the level of fault tolerance of the equipment under control.

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